Sponsored by NASA ESTO
Program: IRaST
Contract Number:

IRaST (Integrate Receiver and Switch Technology

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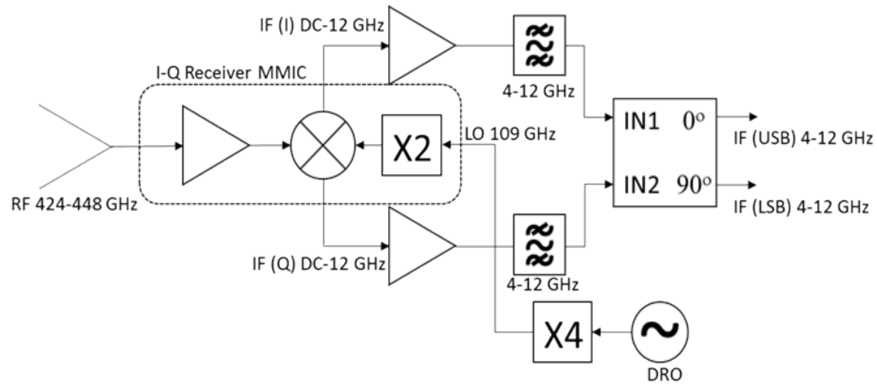
6/3/2021

IRaST Task Overview

Task 1: 424 – 448 GHz Receiver

1. Design a heterodyne receiver for simultaneous observation of 424 GHz oxygen band and 448 GHz water vapor band
2. Minimize Size, Weight and Power (SWaP) with a highly integrated approach, using single multiplier chain to cover both frequencies
3. **Demonstrate applicability to contrail formation**

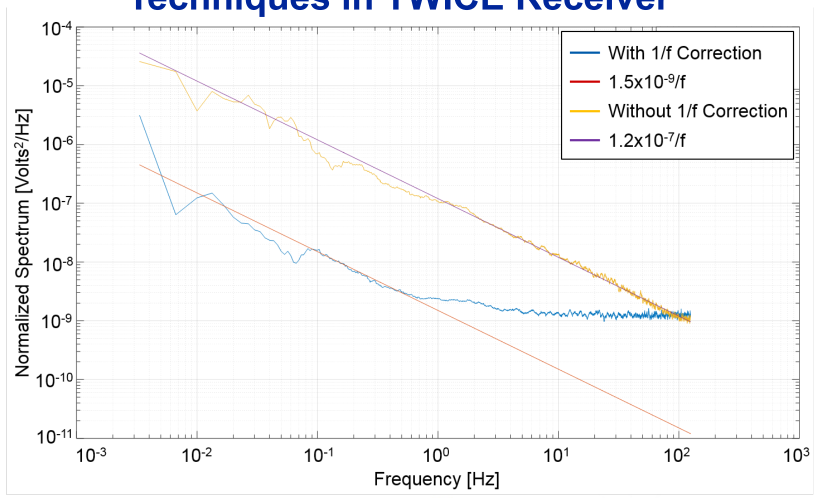
Heterodyne Receiver Block Diagram



Task 2: Switching Technology

1. Develop Integrated Switch technology to eliminate 1/f noise through use of integrated Dicke switches.
2. Develop different architectures of Dicke switches integrated with LNAs to trade off 1/f noise improvement and sensitivity improvement
3. Minimize SWaP using fully integrated receiver MMIC for low cost and performance.

1/f Noise Improvement from Switch Techniques in TWICE Receiver



Integrated Receiver and Switch Technology (IRaST)

PI: Bill Deal/ NGC

Objective

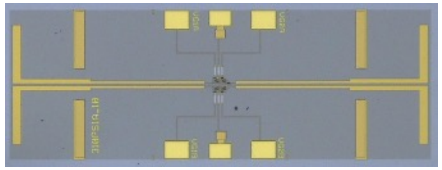
1. Develop Integrated Switch and Phase Shifter technology to eliminate 1/f noise in submillimeter wave direct detection receivers through use of integrated switches.

1b. Develop architectures with integrated switches and noise figures to reduce direct detection 1/f noise

2. Develop upper atmospheric receiver temperature and humidity sounder in single receiver at 424 GHz oxygen line and 448 GHz water vapor line.

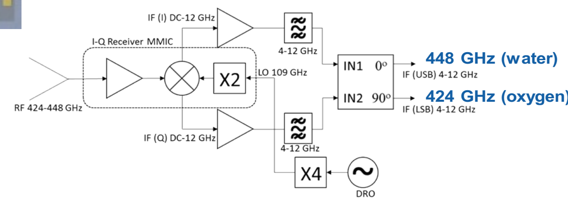
3a. Retrofit MTHP instrument to incorporate 424/448 GHz receiver with the goal of sensing optical thin contrail cirrus clouds

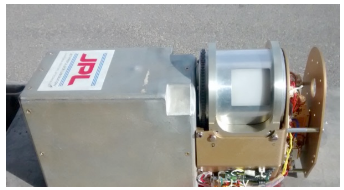
3b. Perform measurement campaign to experimentally measure optically thin contrail cirrus clouds



IC switches and phase shifters will reduce 1/f noise of SMMW direct detection receivers

Integrated 424/448 GHz receiver for sensing water and oxygen





Measure optically thin contrail cirrus clouds vi airborne campaign with modified MTHP profiler

Approach:

Two separate task advance atmospheric science. First, SMMW switch and phase shifters will be demonstrated and there application to reducing direct detection 1/f noise will be examined. Second, advance science of optically thin contrail cirrus clouds with 424/448 GHz airborne measurements.

1. Develop first SMMW IC switches and phase shifters.
2. Develop receiver with simultaneous oxygen and water vapor (424/448 GHz)
3. Integrate 424/448 GHz receiver into MTHP
4. Airborne campaign to verify 424/448 GHz Oxygen and H2O vertical profiles

CoIs: Pekka Kangaslahti, Boon Lim, JPL
Kevin Leong, NGC

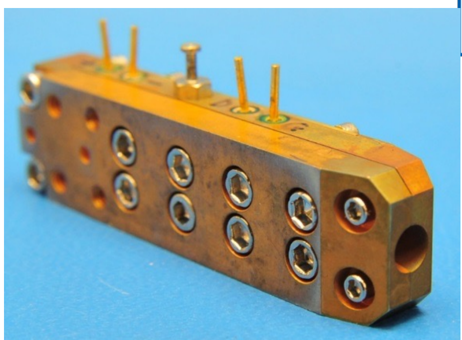
Key Milestones

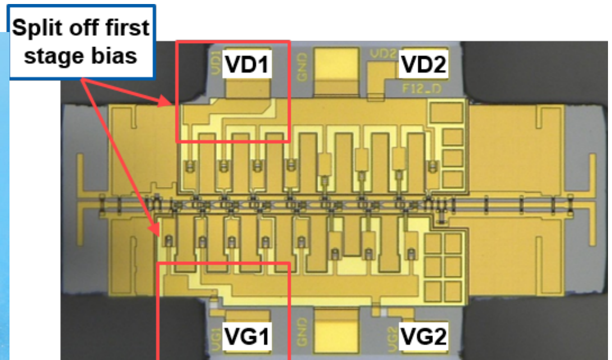
Receiver validation (1st Iter.)	Was: 11/20	Now: 4/21
Second Maskset completion	Was: 1/20	Now: 8/20
Switch validation (2st Iter.)	Was: 5/20	Now: 3/21
Switch Radiometric Validation	Was: 6/20	Now: 3/21
Complete opt. thin contrails sims	Was: 10/20	Now: 12/20
Complete Sys. Requirements	Was: 11/20	Now: 1/21
Complete MTHP mod.	Was: 3/21	Now: 8/21
Complete aircraft integration	Was: 4/21	Now: 9/21
Complete aircraft campaign	Was: 8/21	Now: 12/21
Complete data analysis	Was: 9/21	Now: 1/21

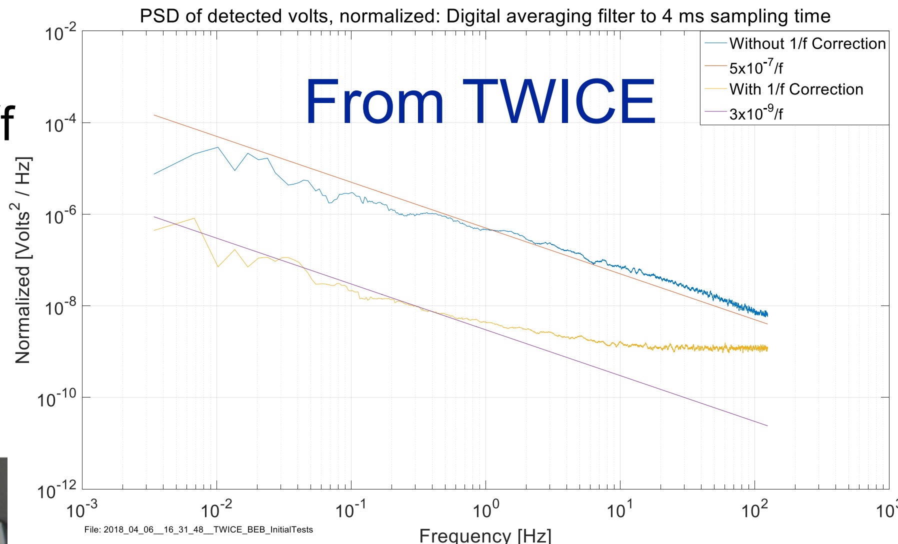
$TRL_{in} = 2$ $TRL_{exit} = 4$

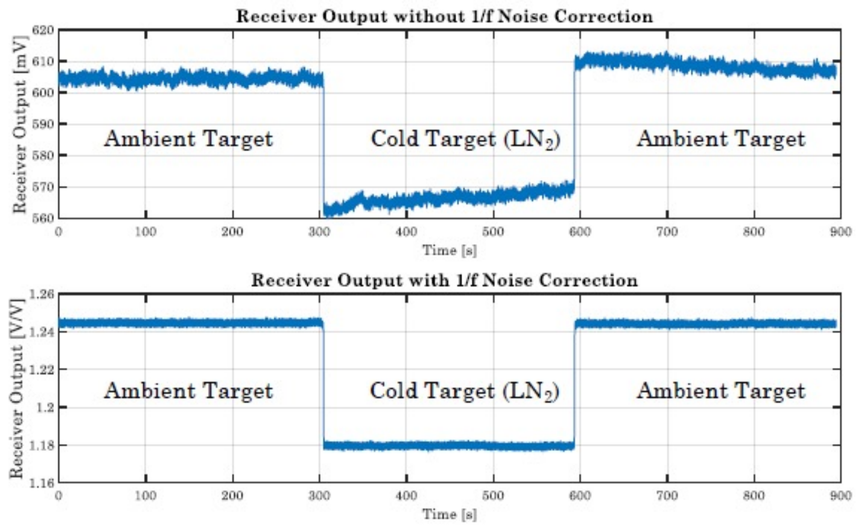
Switch Technology Objective and Approach

- Submillimeter Wave Direct Detection Receivers have excellent SWaP
- But, more prone to NEDT degradation due to 1/f noise
- Initial work on gain switching to lower NEDT performed on TWICE.
- IRaST is investigating other techniques









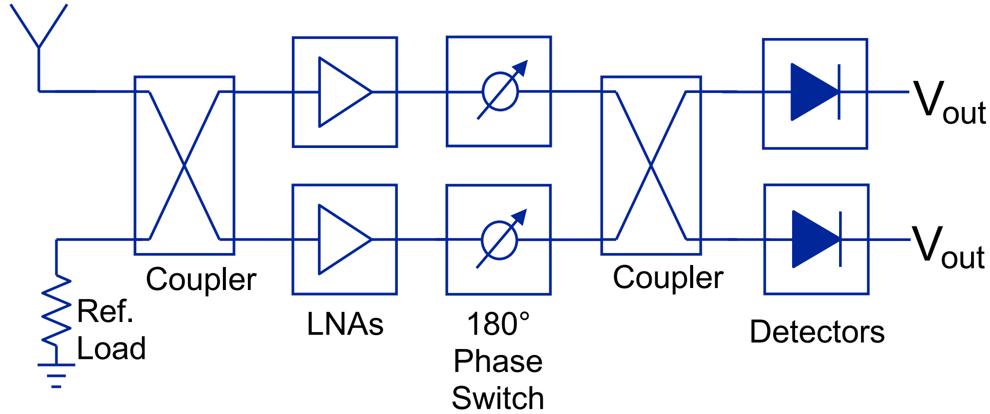
Sensitivity Results with 50 msec Integration Time

NEΔT Without Switching	NEΔT With Switching
4.75 K	0.88 K

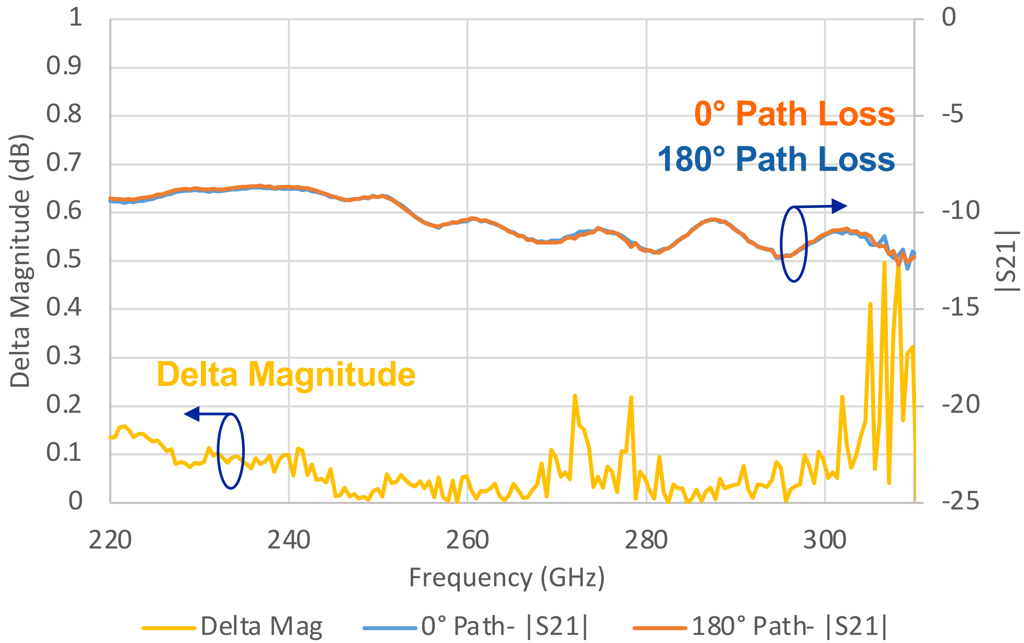
- M. Ogut, C. Cooke, W. Deal, P. Kangaslahti, A. Tanner, and S. C. Reising, "A Novel 1/f Noise Mitigation Technique Applied to 670 GHz Receiver," *Submitted: IEEE Trans. On Terahertz Science and Technology.*

Pseudo-Correlator

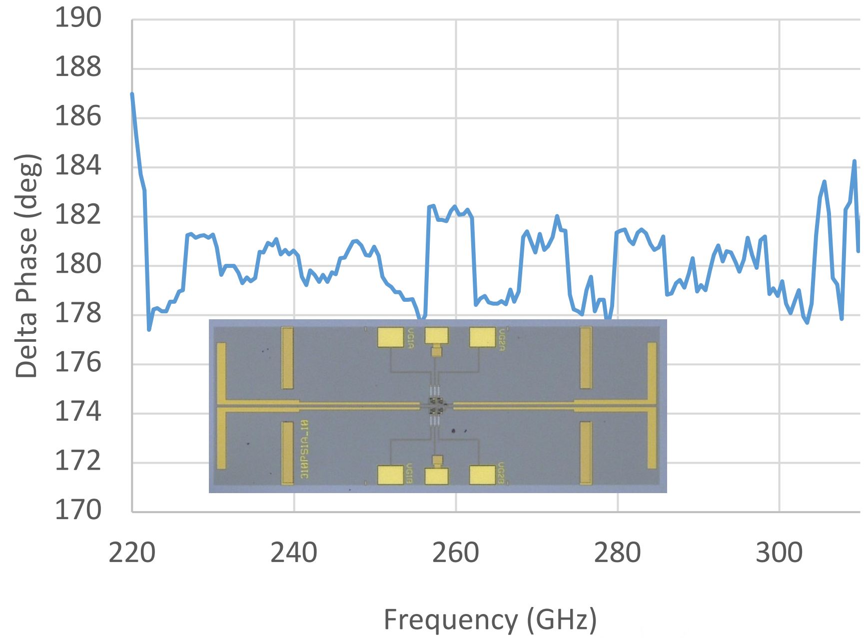
- Pseudo-correlator can reduce 1/f noise and eliminate sqrt(2) NEDT impact from switching
- Requires development of 180 degree phase switches
- Have demonstrated that to



Delta Insertion Loss Between 0° and 180° Paths



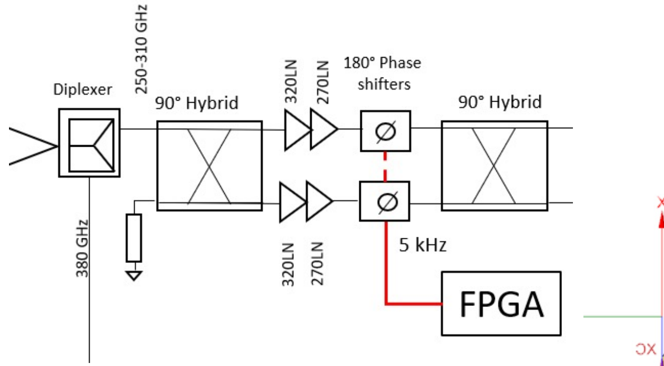
Phase Delta



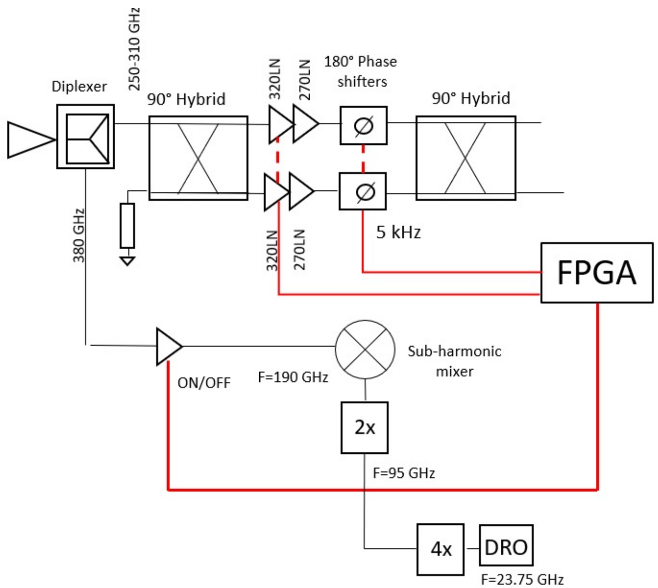
SMICES 250/310/380 GHz RF Module: 1/f gain fluctuation mitigation strategies

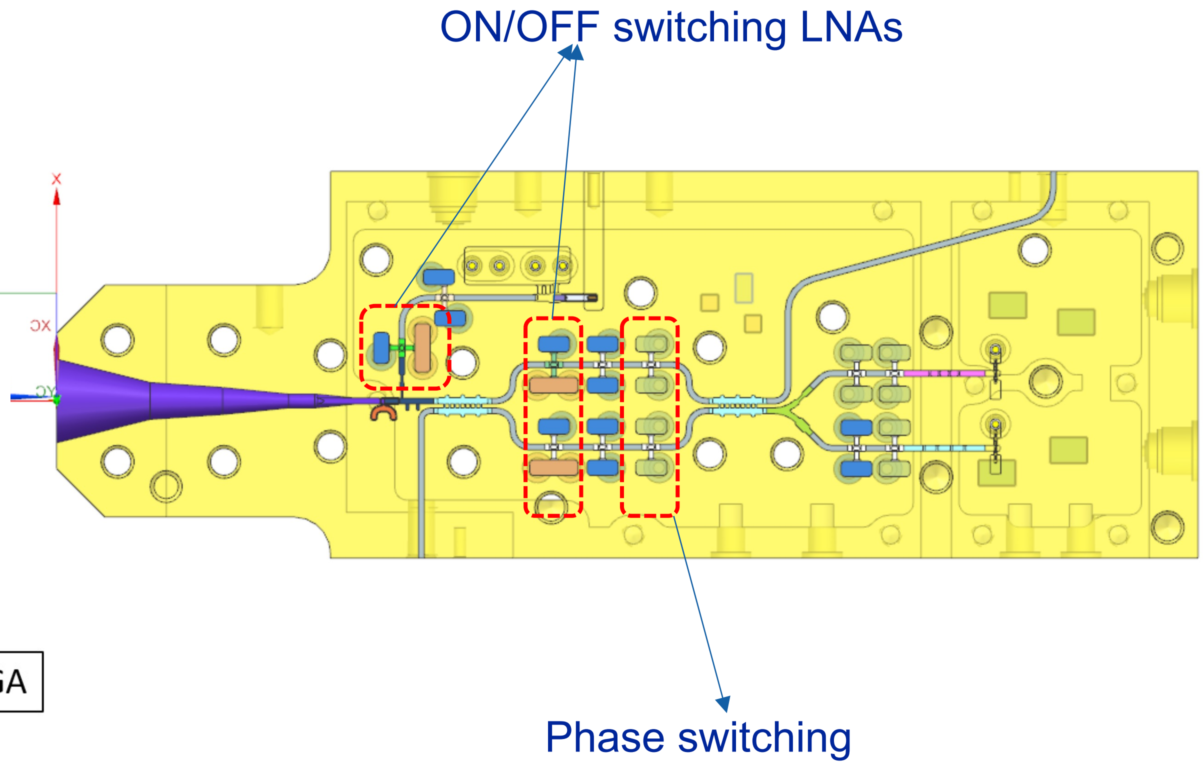
- 250/310 GHz channels:
  - primary solution pseudo-correlation architecture with phase switching, and
  - a secondary solution ON/OFF switching the first LNA.
- 380 GHz channel with ON/OFF switching the first LNA.

Pseudo-correlation architecture with phase switching

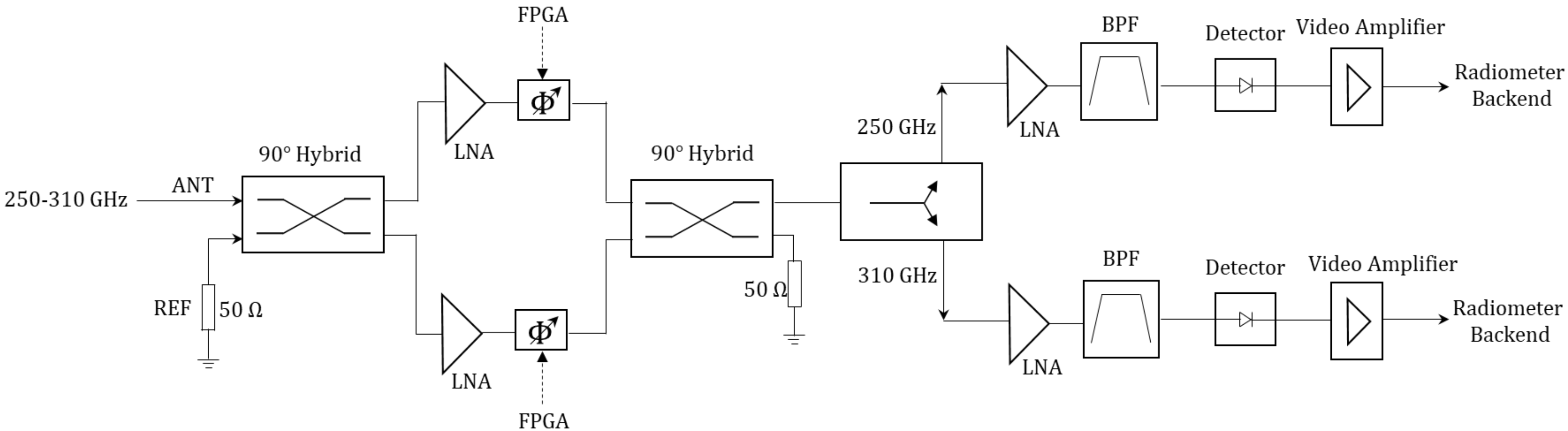


ON/OFF architecture switching the first LNA





SMICES Pseudo-Correlation Radiometer: Receiver Calibration



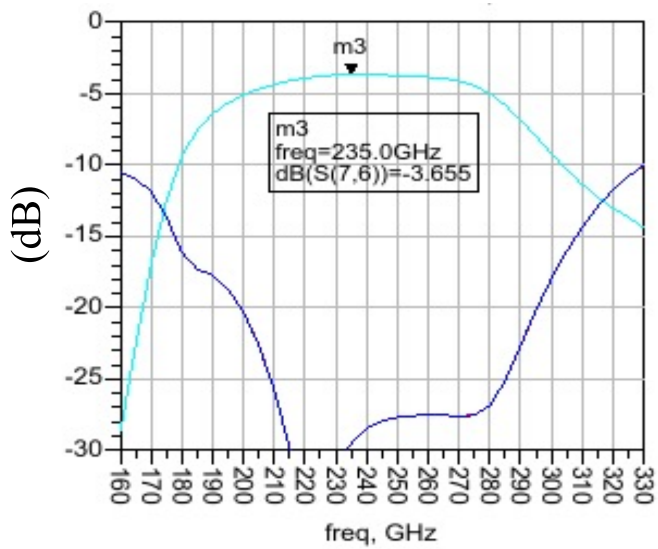
Radiometric Data Acquisition Process for Pseudo-Correlator Calibration:

- 90° Hybrid Design: It eliminates the need for a Dicke-switch to acquire antenna and reference samples. Instead, antenna and reference samples are both transmitted thru hybrid all the time.
- Phase shifters: The switch is controlled by FPGA to generate phase alternating between 0° and 180°. This will provide antenna or reference signals acquired at the radiometer backend for 250 GHz and 310 GHz receivers.
- Post-processing: This novel design enables us to perform Dicke-type calibration at high-frequency receiver channels to mitigate 1/f noise.

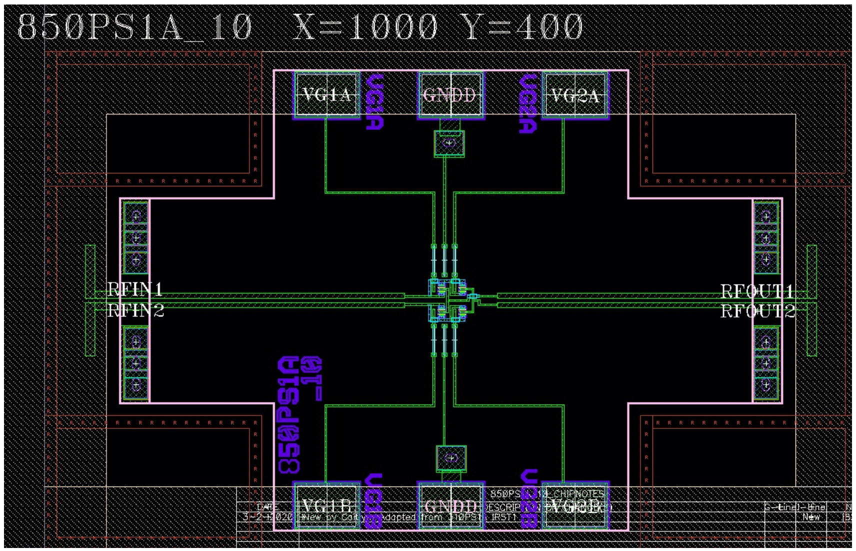
IRST2 Designs: Phase Shifter Simulations

- Fundamental to the pseudo-correlator receiver architecture
- Series shifter validated at 230 GHz on IRST1
- Series phase shifter designed from 230 to 850 GHz
- Parallel phase shifter designed from 230 to 670 GHz
- Parallel transistor configuration has lower loss, trade-off with narrower bandwidth

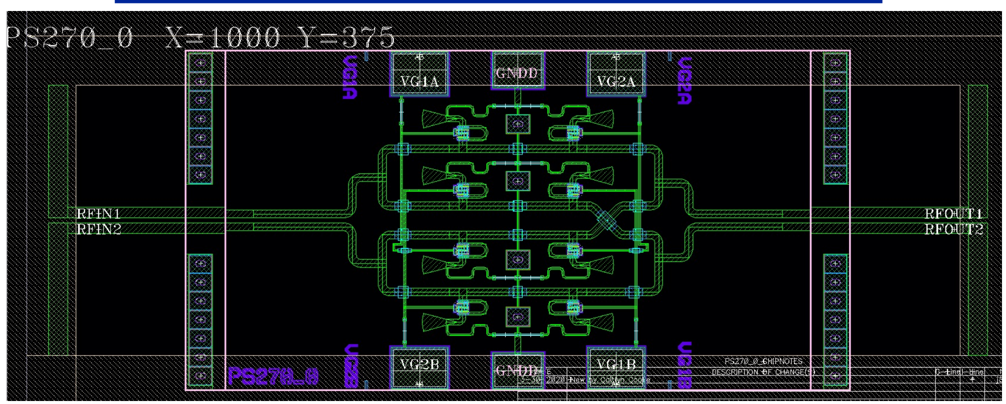
Parallel Shifter Thru Loss and Isolation



850 GHz Series Phase Shifter



230 GHz Parallel Phase Shifter Layout



424/448 GHz Integrated Receiver Application

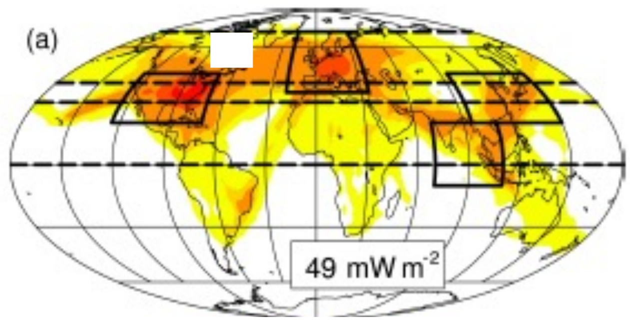
- **Air pressure** and **humidity** two driving forces behind the creation of airline contrails in the upper atmosphere
- **The IRaST 424/448 GHz receiver may be very well suited for sensing conditions for contrail formation**
- **We will discuss this more at the Annual PI review**
- Simultaneous observation of 424 GHz and 448 GHz channels
  - 424 GHz oxygen = measure of **temperature**
  - 448 GHz water vapor = measure of **humidity**

- Study released predicting the impacts of contrail formation on climate change
  - L. Bock, U. Burkhardt, "Contrail cirrus radiative forcing for future air traffic", *Atmospheric Chemistry and Physics*, vol. 19, pp. 8163-8174, Jun. 2019.

Increase in Radiative Forcing due to airline contrails
(from L. Bock, U. Burkhart, 2019)

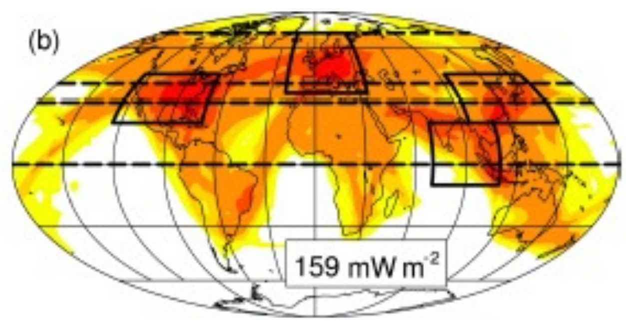
Baseline (2006)

(a)



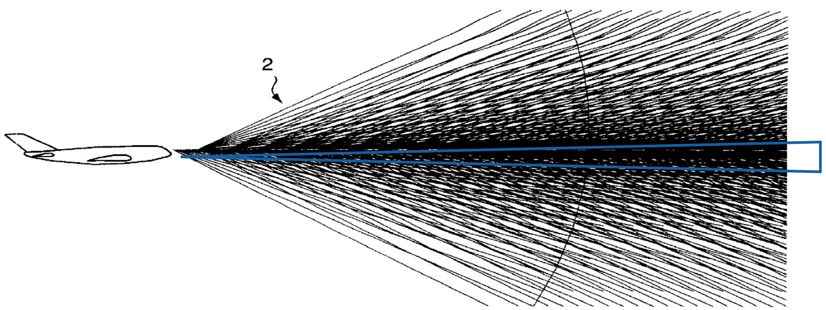
Increase by 2050

(b)



Contrail Sensing Demo

- Optically thin contrail cirrus clouds caused by commercial aircraft is being attributed to ~5% of global warming
- This is effect is expected to increase over time as frequency of commercial flights increase.
- Contrail formation conditions are related to temperature, humidity, and water vapor left by aircraft jet exhaust
- The IRaST 424/448 GHz receiver was chosen to profile the oxygen and H20 lines at altitudes typical of commercial aircraft flight
- The IRaST Contrail Demo will:
  - Perform forward vertical profiling for temperature and humidity
  - Correlate to aircraft data
  - Correlate on-aircraft contrail data to data on Contrail data collected by NGC GII aircraft



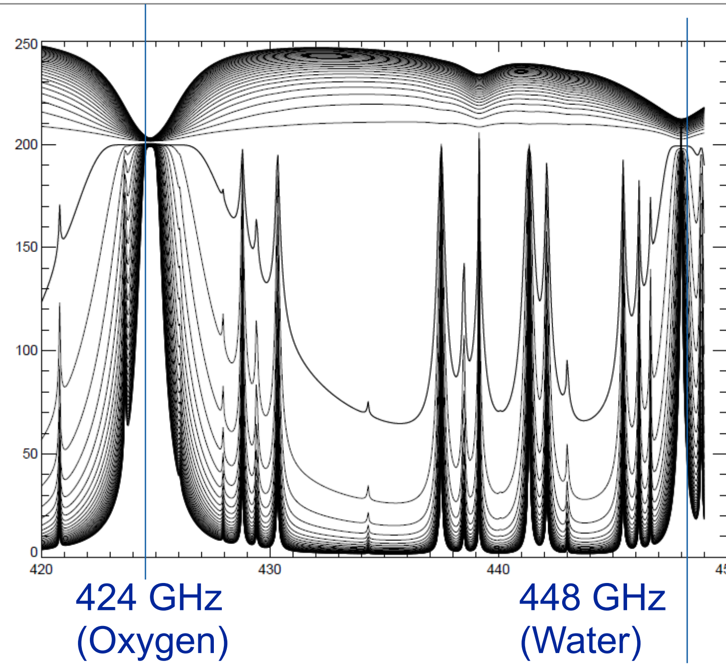
Scan forward zenith-to-nadir to measure water and T profile

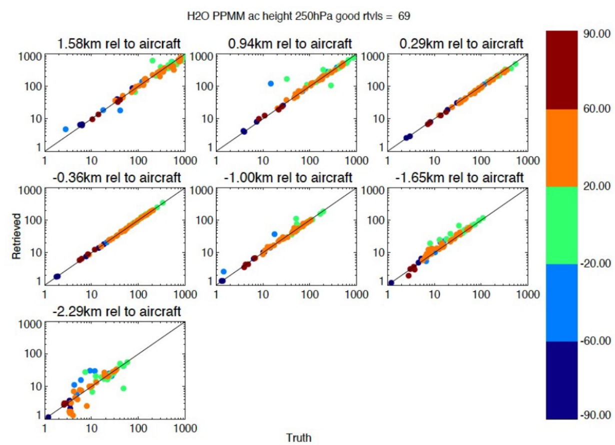
<u>Northrop Grumman GII Aircraft Configuration:</u>

- Full suite of sensors for contrail sensing
- Humidity and temperature sensing
- LIDAR will sense when contrails are formed
- MTHP/IRAST will forward profile and correlate to data on GII aircraft.

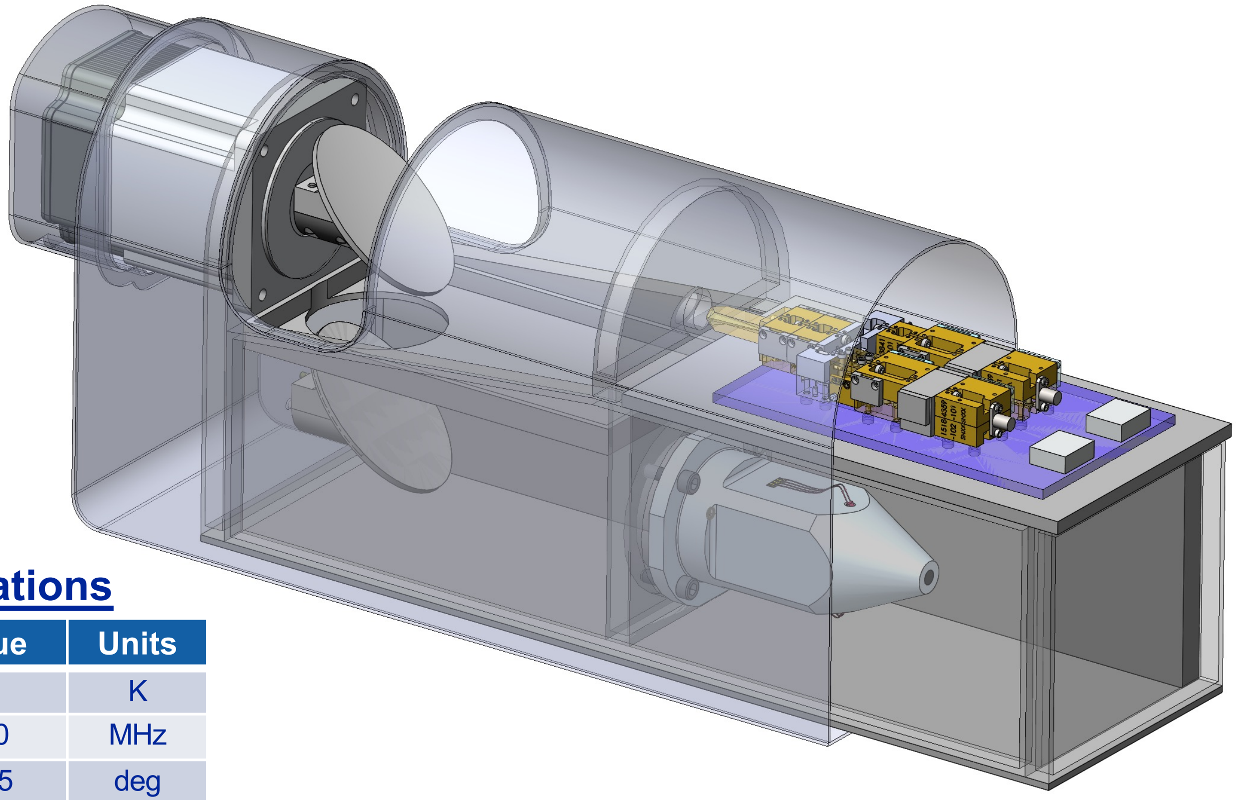
Contrail Formation

- Contrail formation is a function of humidity and pressure
- Aircraft contributes additional water vapor from exhaust
- Have done initial simulations to help specify instrument
- Additional work will be done when data is gathered after aircraft campaign





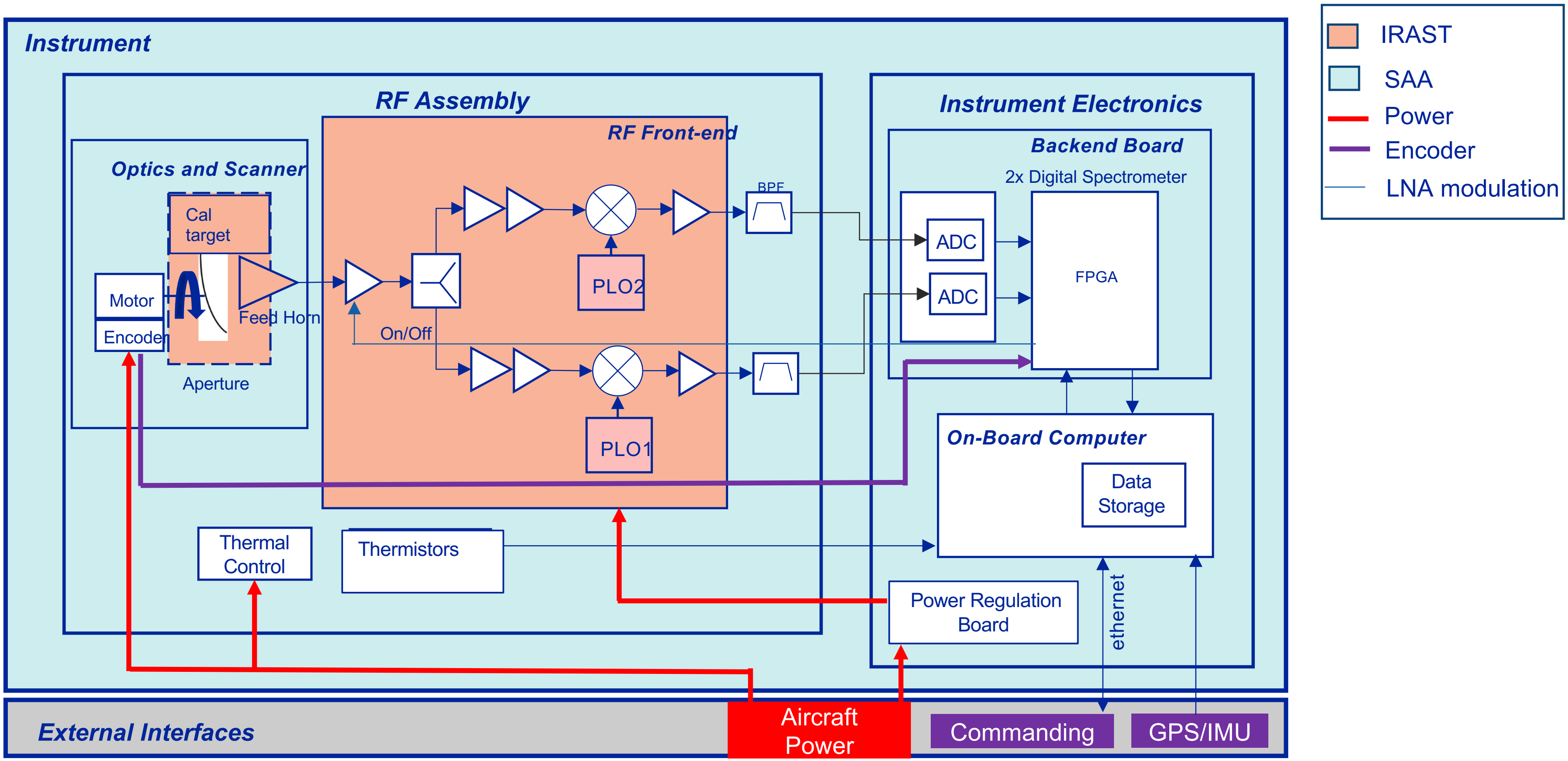
Instrument Overview (in progress)



Instrument Specifications

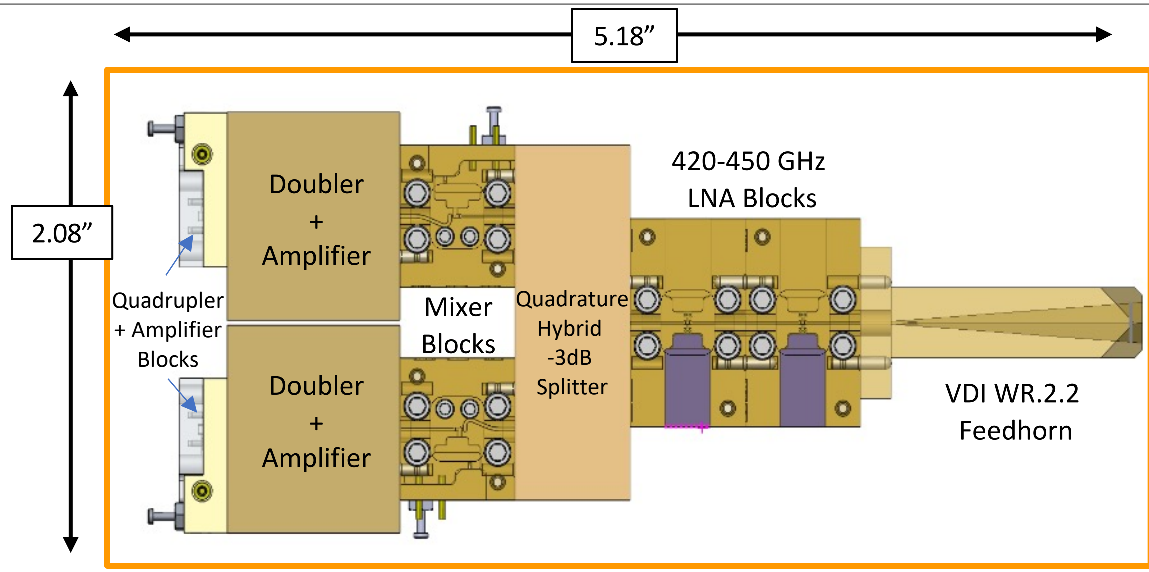
Specification	Value	Units
NEDT	1	K
Bandwidth	100	MHz
Half Power Beamwidth	0.75	deg
Integration Time	50	mSec
Observation Time	1	Sec
Calibration Time (load and sky)	0.5	Sec
Motor Movement Time	0.3	Sec
Total Sweep Time	1.8	Sec
Sweep Angle	20 +/- 10	deg
DC Power Consumption	< 8	W

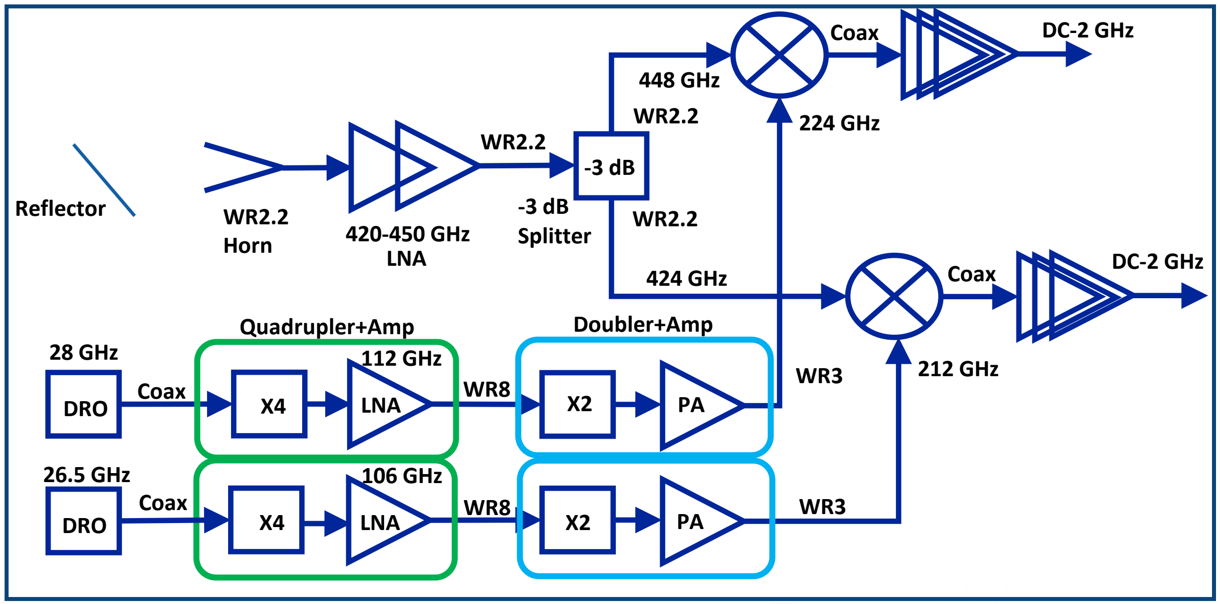
Instrument Block Diagram



424/448 GHz Receiver Approach

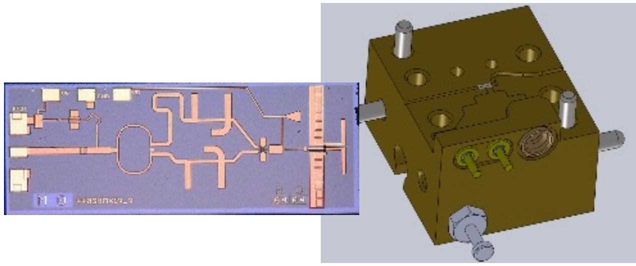
- Instrument reflector feeds single VDI WR-2.2 feedhorn
- Wideband front-end RF LNAs, single LNA per module
- 3 dB power splitter module splits 448 GHz and 424 GHz channels
- Each channel contains respective mixer module
- Coax mixer output feeds COTS IF amplifier
- Each channel LO chain contains active doubler module, active quadrupler module, DRO
- Leverages NG 25 nm InP HEMT process for RF and LO amps, multiplier chains, and mixers
  - Full chipsets on IRST1 and IRST2 wafer fabrication runs





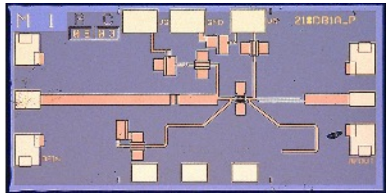
Component Simulations

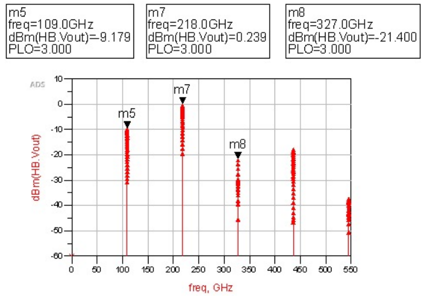
WR-2.2 Mixer



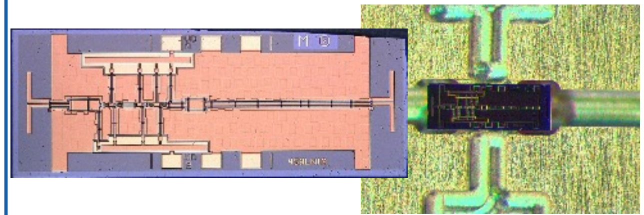
Simulated Specifications	
Bandwidth	424 – 448 GHz
Conversion Gain	-17 dB
LO power	0 dBm
Output Waveguide	WR-2.2

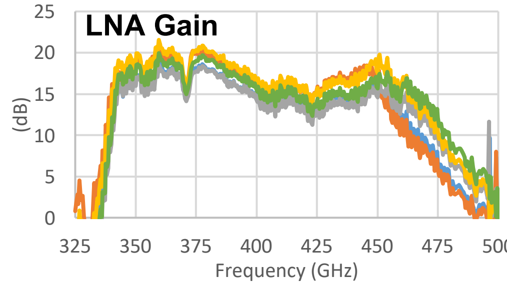
218 GHz Doubler



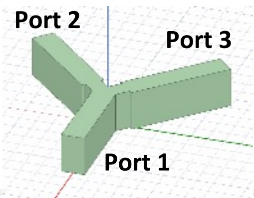


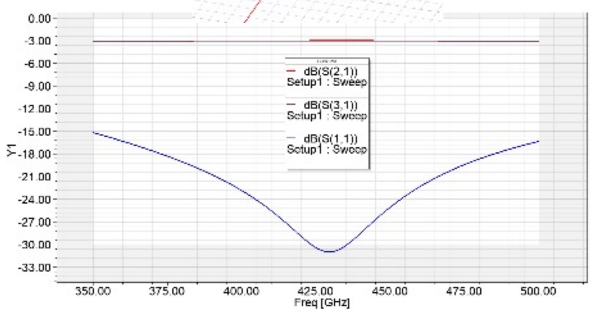
WR-2.2 LNA



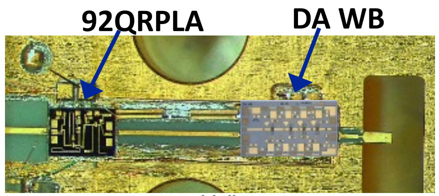


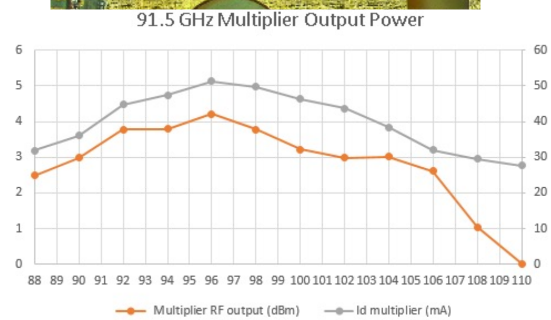
WR-2.2 3 dB Splitter



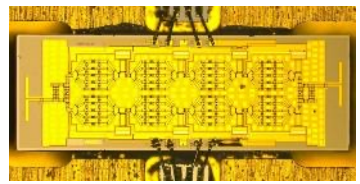


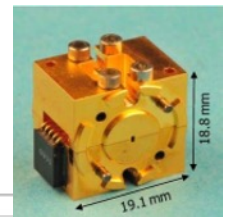
Legacy WR-8 Quadrupler

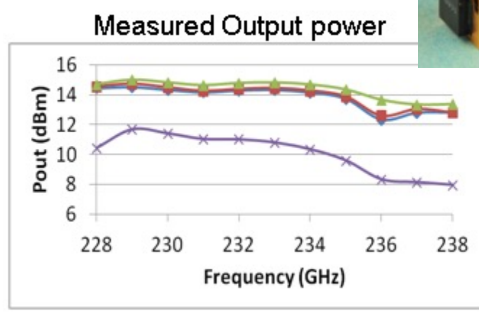




Legacy WR-4.3 PA

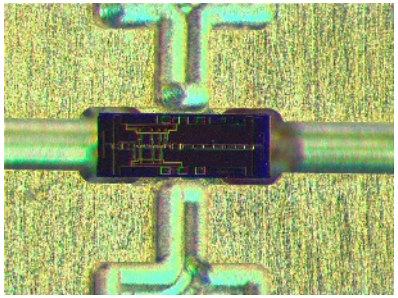


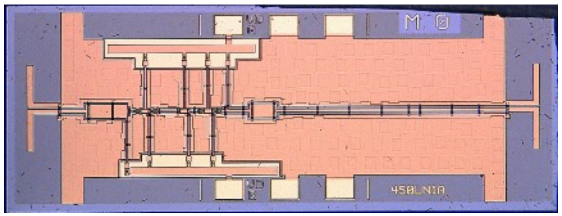




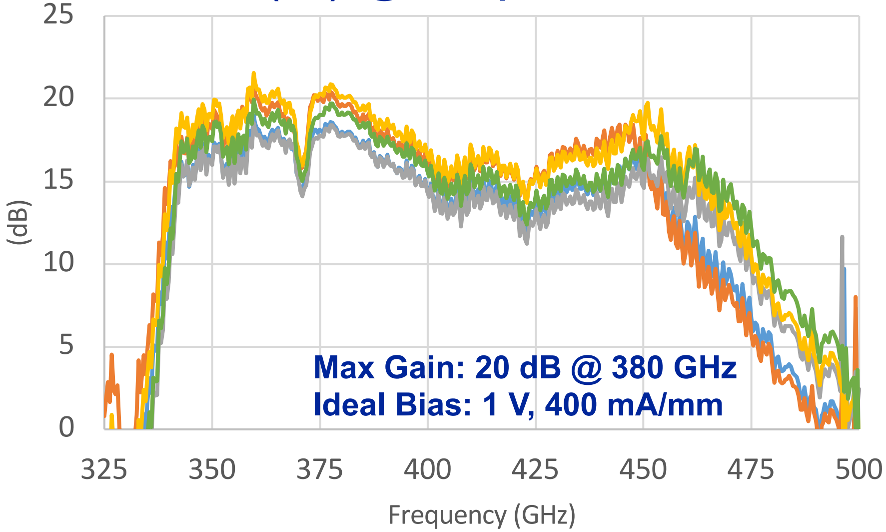
425 GHz LNA Measurements (Preliminary)

- NGs legacy 425 GHz chip measured in WR-2.8 test package
- Performance degradation at high frequency due to WR-2.8 housing dipole transition



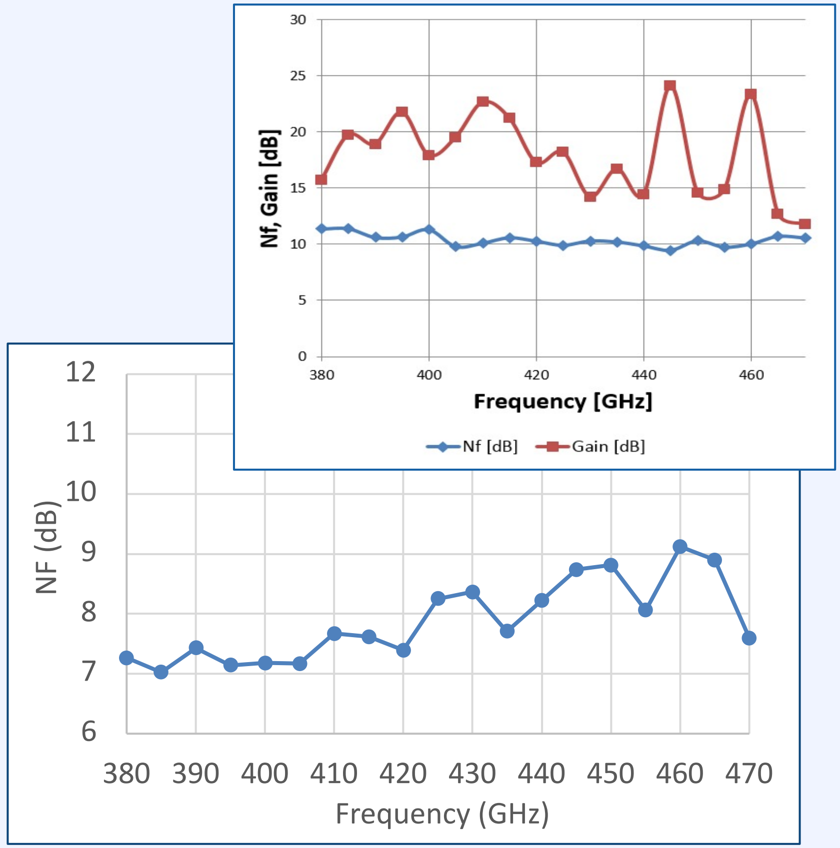


Gain (dB): @ Multiple Bias Points



NF (dB): 1 V 400 mA/mm Bias

- Up to 3 dB improvement with 25 nm process
- Min NF: 7.02 dB @ 385 GHz
- 8.25 dB @ 425 GHz
- 8.8 dB @ 450 GHz



3 dB Noise Figure Improvement from Legacy Terahertz Process

Wrapup

- Significant work has been done on IRaST to develop new techniques for reducing 1/f noise in direct detection receivers (improved NEDT)
  - 2nd maskset completes fabrication by June 20th
  - Techniques are being incorporated into SMICES
- The IRaST 424/448 GHz receiver is now being designed into an updated MTHP instrument
- Instrument will be flown on NGG GII aircraft to evaluate contrail formation

Acknowledgements:

- “Thank you” to all of the contributors at NGC, JPL, and NASA ESTF to help make this work happen

Earth Science Technology Office

NORTHROP GRUMMAN